Experimental validation of the Finite Element Simulation of the First Stroke in Single Point Incremental Forming

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ABSTRACT: Single-point incremental forming (SPIF) is a sheet metal forming technique that has gained particular interest in rapid prototyping and small volume production. The study of the underlying forming mechanisms is supported by new developments in finite element simulations and experimental full field strain measurements. This article aims to describe the possibilities and difficulties encountered during validation of finite element predictions of the incremental forming process. The drawing of a straight line into a metal plate was selected as a first test case for this kind of validation. Results of both finite element simulation and experimental work will be discussed.

Key words: finite element, incremental forming, digital image correlation, sheet metal

1 INTRODUCTION

Incremental forming is a generalized term of metal forming processes where tools of common shapes are used to form a small portion of the work piece consecutively next to another resulting in a desired shape. Where die-sets are exclusively designed for particular shapes, one can produce complex forms using a combination of a simple tool and a simplified die. [1,2,5,6]
Although ordinary press forming requires less time and is more cost effective in large series production than incremental forming, this new process offers interesting perspectives in small volume production and rapid prototyping [1,2,5,6]

Several departments of the above mentioned universities have joined into a research project on the fundamental understanding of the underlying mechanisms of incremental forming. Recent developments in both finite element simulations and full field strain measurements such as Digital Image Correlation Techniques (DICT) enable to investigate the SPIF-process in detail. Although numerically predicted deformations have considerably gained importance, it is still good practise to validate the obtained results by experiments.

This paper describes some possibilities and difficulties encountered during a first stroke in incremental forming. The experiment is performed in both reality and numerical space, after which some results were compared in a few points of interest. This investigation must be seen as a first step for the validation of the entire incremental forming procedure.

Important for this article is to mention that whenever strain is concerned, it is about true strain.

2 EXPERIMENTAL SET-UP

In order to be able to compare simulation results with experimental data, all geometrical and material parameters in both numerical space and reality should be kept the same. The considered first stroke (a straight line) set-up is shown in Fig. 1.

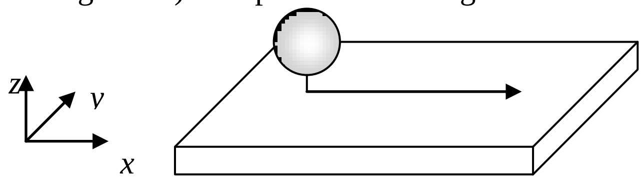

Fig. 1 - Tool path generated during experiment and simulation

The spherical tool (∅ 12.7 mm, material: tool steel, Vanadis 23) draws a straight line (depth 5 mm) over a length of 100 mm. The 1.2 mm thick Al3003 square sheet is considered to be clamped at all edges. The size of the plate is 182 mm x 182 mm. The start point is situated at x = 41 mm and y = 91 mm, the endpoint at x = 141 mm and y = 91. The friction coefficient was estimated at a value of 0.05.

2.1 Incremental forming set-up

The tool is controlled by a conventional 3-axis CNC milling machine (MAHO 500), while a moving special blank holder guarantees the clamping condition at the edges. The feed rate was set to 1000 mm/min and the spindle was fixed. Friction was minimised using oil. A more detailed description can be found in [3]

2.2 Numerical simulation

For the numerical simulations a finite element code called "Lagamine" is used. Lagamine is developed at the dept. M&S of the University of Liège. More details about this software can be found in [3].

The aluminium sheet is modelled by 15 x 30 elements, taking advantage of the symmetry of the process along the y-axis. The elements are 8-node isoparametric brick elements with an anisotropic Hill type law. Three layers of these elements were chosen along the thickness, as a result of a compromise between computation time and precision.

2.3 Digital Image Correlation Technique

Experimental strain and displacement fields were obtained using the optical LIMESS [4] measurement system. This equipment allows taking several frames of the object of interest using a Charge Coupled Device (CCD) camera. Each frame corresponds to a different loading position. A random black and white speckle pattern was applied onto the bottom side of the aluminium plate. After choosing selected facets in the undeformed frame, an image correlation algorithm allows finding their new position and orientation in the deformed frame. A facet typically contains 15 x 15 pixels. Identification software next identifies the displacement and deformation of all the selected facets yielding a displacement field. The strain field can be computed from the identified displacement field. More technical details about this method can be found in [4].

2.4 Adapted test procedure

A major difficulty encountered with the test set-up was that the tool is fixed on the milling machine while the blank holder moves. Due to vibration problems it appeared impossible to mount the camera on the blank holder. Therefore it was decided for this initial test to compare the undeformed state to the deformed one after unloading. This procedure enables thus to measure the plastic deformations but gives no information about the total deformations (elastic + plastic) during loading.

3 NUMERICAL SIMULATION

3.1 Results

Numerical simulations return a wide number of data of which only a few can actually be compared with experimental obtained parameters. The biggest challenge for researchers today is not to acquire as much as possible data - which is quite easy – but to gain relevant data.

For this experiment, the evolution of the equivalent von Mises strain during simulation was studied. Its value is represented in the bottom layer for two different times in Fig. 2a and b.

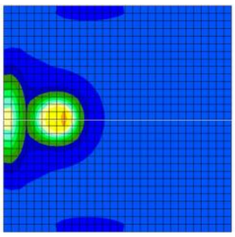

Fig. 2a. – Equivalent strain at start point (depth tool: 5 mm)

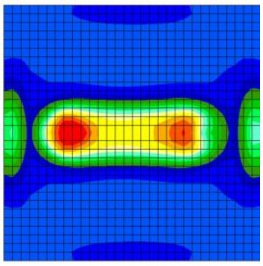

Fig. 2b. – Equivalent strain after deformation (tool removed)

From Fig 2a and b. is noted that the zones around the start and end point strongly differ from the middle of the path, which appears to be uniform along the tool path. Three zones of interest were therefore selected: the start (A), the end point (C) and a point (B) in the middle.

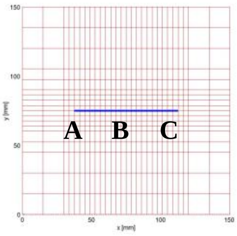

Fig. 3. – Definition of 3 points for the numerical simulation

Strain evolution in these three points can be analyzed for every time step, resulting in Fig. 4a to c. ε_x is the true strain in the direction of the tool path, ε_y is the in-plane strain perpendicular to the tool path and ε_z is the relative change in thickness.

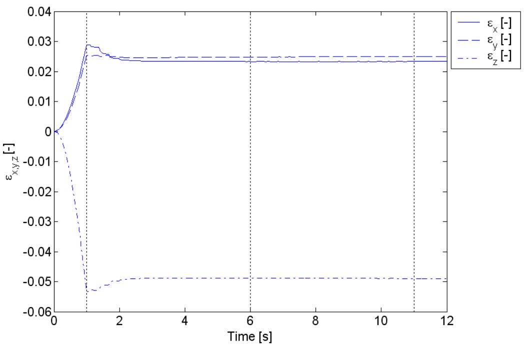

Fig. 4a. – Evolution of total strain in point A over time

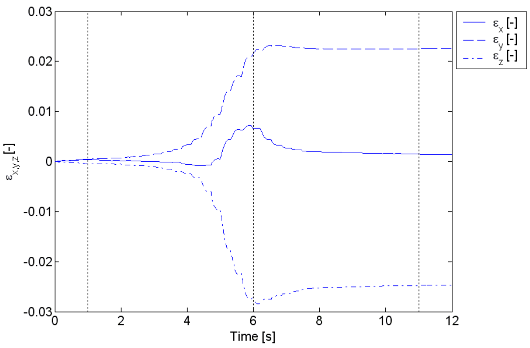

Fig. 4b. – Evolution of total strain in point B over time

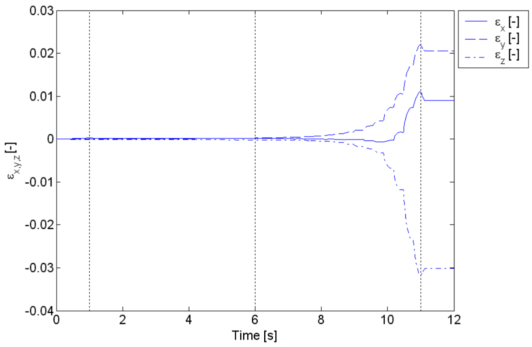

Fig. 4c. – Evolution of total strain in point C over time

From these figures it is clear that the effect of the deformation is very local. The size of the influenced zone around the tool is less than twice the diameter of the tool. After the tool has been removed, only the plastic strain component remains. It can be seen that the elastic component is neglectible.

Analyzing strains in points A, B, C results in table:

Table 1. Plastic strain components after deformation obtained with the numerical simulation for three selected points

	ε_x (%)	ε_y (%)
A	2,38	2,51
B	0,053	2,22
C	0,893	2,06

These results confirm assumption and observations made by previous authors ([1],[2]) that plastic deformation for incremental forming is a plain strain situation for the residual deformations. At the end points of the path a situation of biaxial stretching was observed, as was described in [2].

4 EXPERIMENTAL RESULTS

Fig.5a and b show the remaining strain after loading (i.e. plastic strain). In this case, ε_x and ε_y are defined the same way as for the numerical simulations.

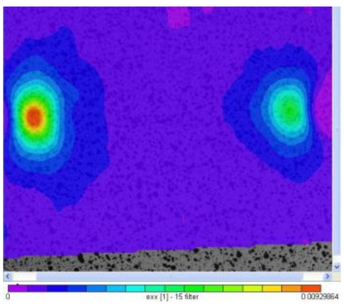

Fig. 5a. – Experimentally measured ε_x -field

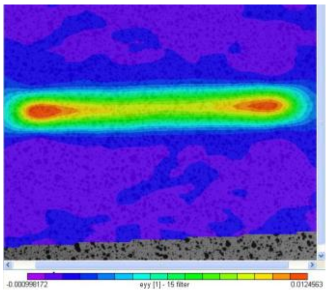

Fig. 5b. – Experimentally measured ε_y -field

With LIMESS it is possible to select points or zones of interest for the analysis of the strains. This was done for 4 identical experiments of which Table 2 shows the averaged results. During the analysis a rejection criterion was used to eliminate outlyers results due to poor facet correlation. One of the five tests was eliminated. Identification on the specimens of points A, B and C, as were defined in the numerical simulation, reveals that:

Table 2. Plastic strain components after deformation obtained for the same three selected points as in the simulation

	ε_x (%)	$\Delta\varepsilon_x$ (%)	ε_y (%)	$\Delta\varepsilon_y$ (%)
A	1,0	0,2	1,3	0,1
B	0,07	0,04	1,0	0,2
C	0,40	0,07	1,1	0,3

$\Delta\varepsilon$ is the largest difference between a measurement and the average. These experimental results will be compared with the numerical simulation in the following paragraph.

5 DISCUSSION

Analyzing stretch patterns on both numerical simulation and experimental work show qualitative resemblance and return strain fields that could be expected. Comparison of the quantitative data, however, shows a large difference between the strain values of Table 1 and Table 2.

These large differences reveal the difficulties occurring in the validation and simulation of a small initial step of the incremental forming process:

- Boundary conditions have a large influence on the results: sliding between the blank specimen and the clamping device causes much smaller strains than calculated.
- The sheet is initially not perfectly flat, with great consequences on out-of –plane deformations and thus the strains.
- Other simulations of SPIF concluded large differences at initial contacts between tool and sheet [3]. This experiment is in fact such a first contact and this could also explain this gap between reality and simulation.

A difficulty in validating numerical results is the correct matching of observed points to nodes in a FE simulation. For this case the identification however was quite simple, because start and end point were easy to identify. However, more complex tool paths will require more adapted interface methods.

The experiment confirmed earlier conclusions [1] about the strain distribution: biaxial stretching at end points as well as plain (plastic) strain in the middle of the path was observed during this experiment.

6 CONCLUSIONS

This experiment was a first step in a larger program to validate numerical simulations of SPIF with a DIC-technique. It is clear to the authors that DICT has great potential for this kind of comparison. Qualitative conclusions made in previous articles were confirmed both by simulation and experimental observation.
Comparison between numerical and experimental results showed a large discrepancy. Further research on the causes of the discrepancies is absolutely necessary. This article underlines the importance of validation of numerical models by experiments.

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